SWOT Estimation of Surface Velocity and Vorticity

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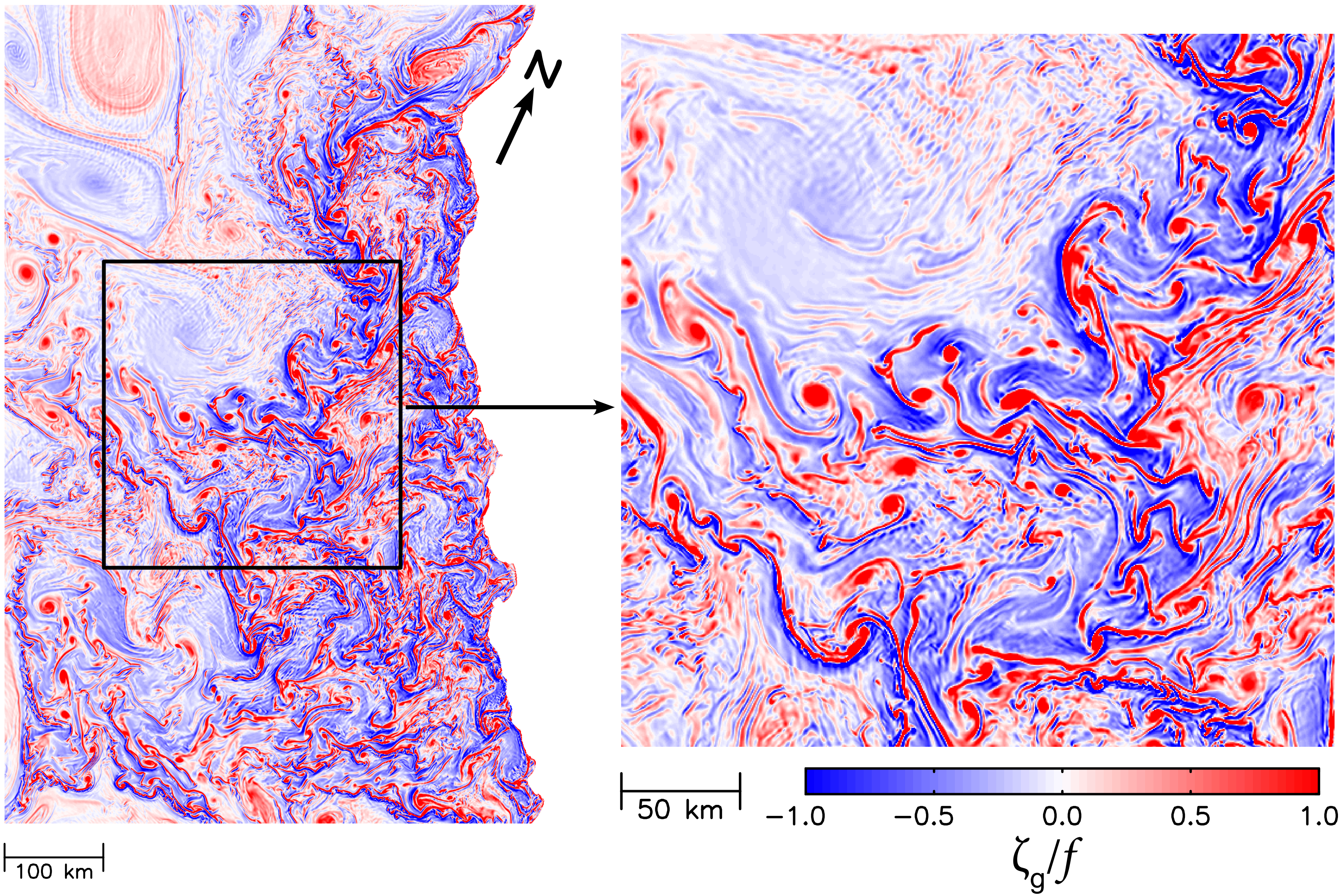
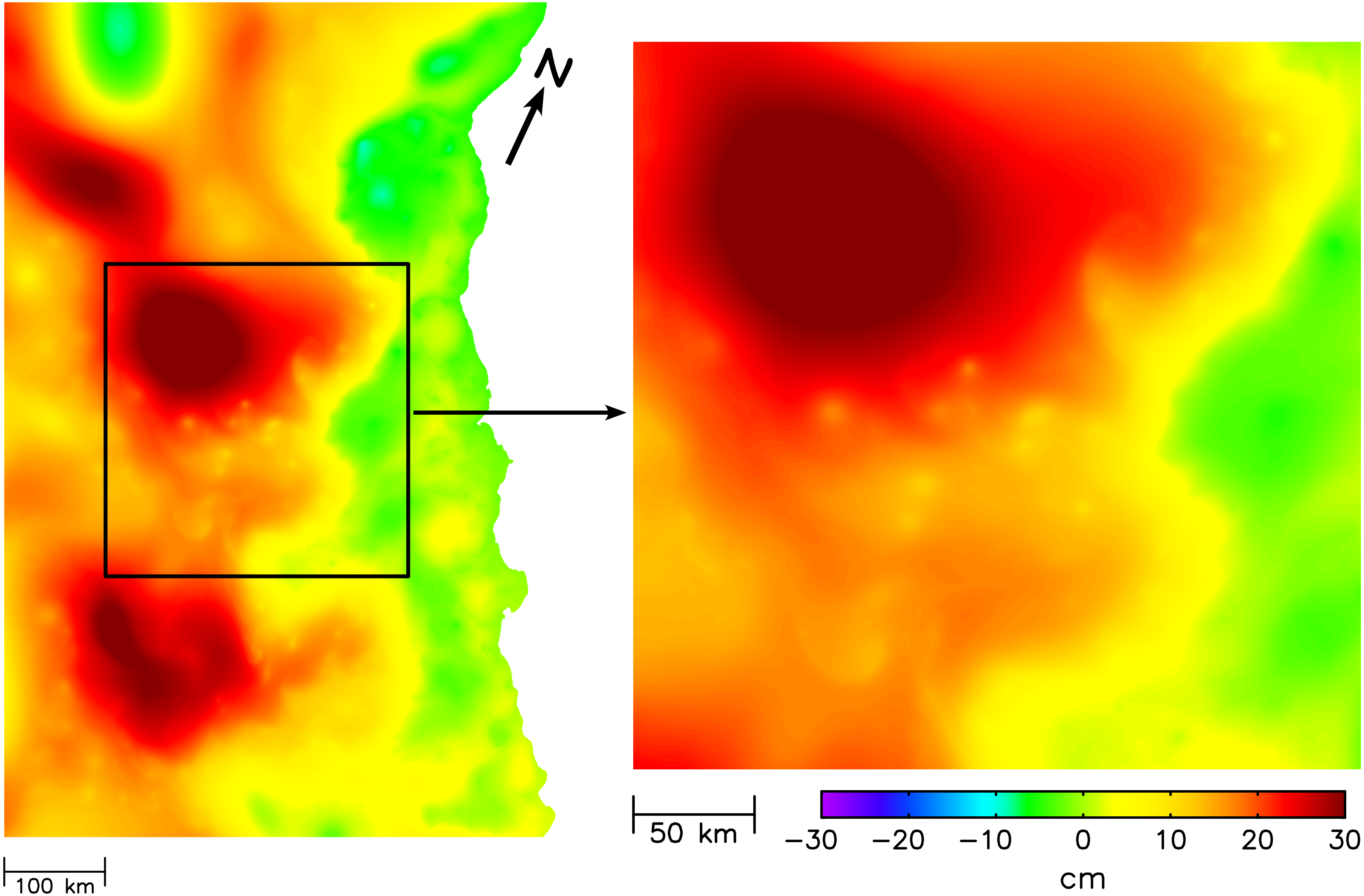
Geostrophic Vorticity from a Model of the CCS with 0.5 km Grid, Smoothed to 1 km Resolution of SWOT

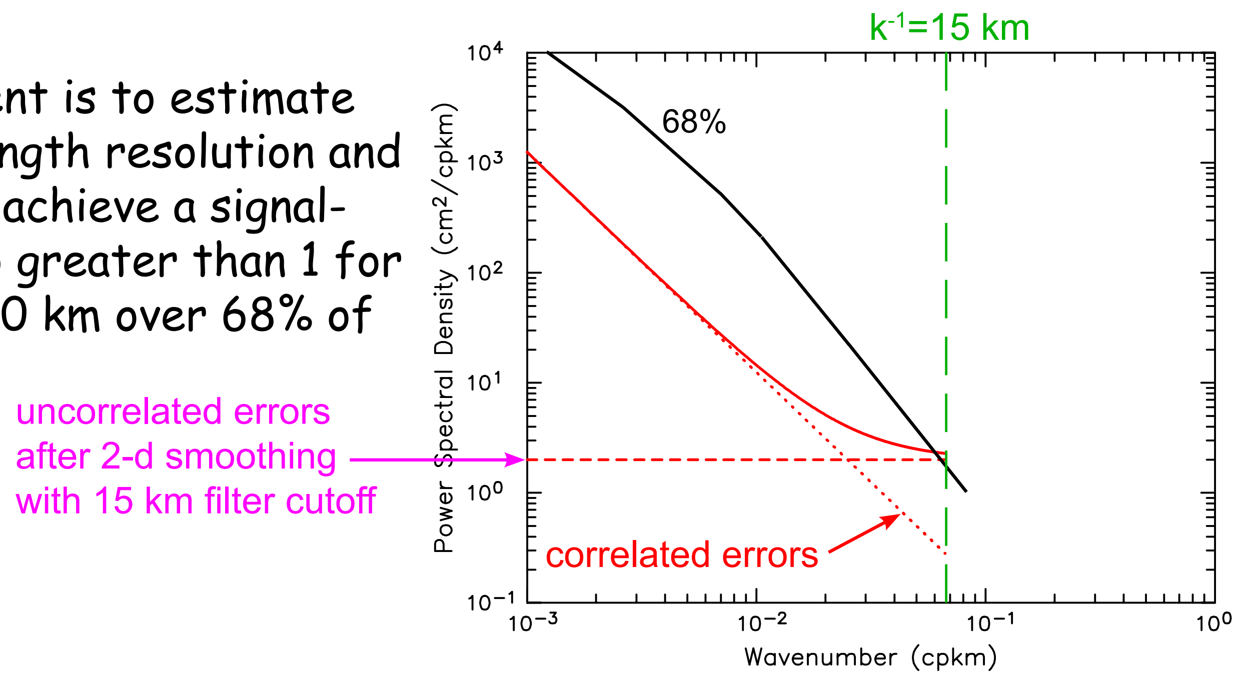


Sea Surface Height from a Model of the CCS with 0.5 km Grid, Smoothed to 1 km Resolution of SWOT



Error Analysis for SWOT Estimates of SSH, Geostrophic Velocity and Geostrophic Vorticity

The science requirement is to estimate SSH with 2 km wavelength resolution and sufficient accuracy to achieve a signal-to-noise variance ratio greater than 1 for wavelengths of 15–1000 km over 68% of the world ocean.



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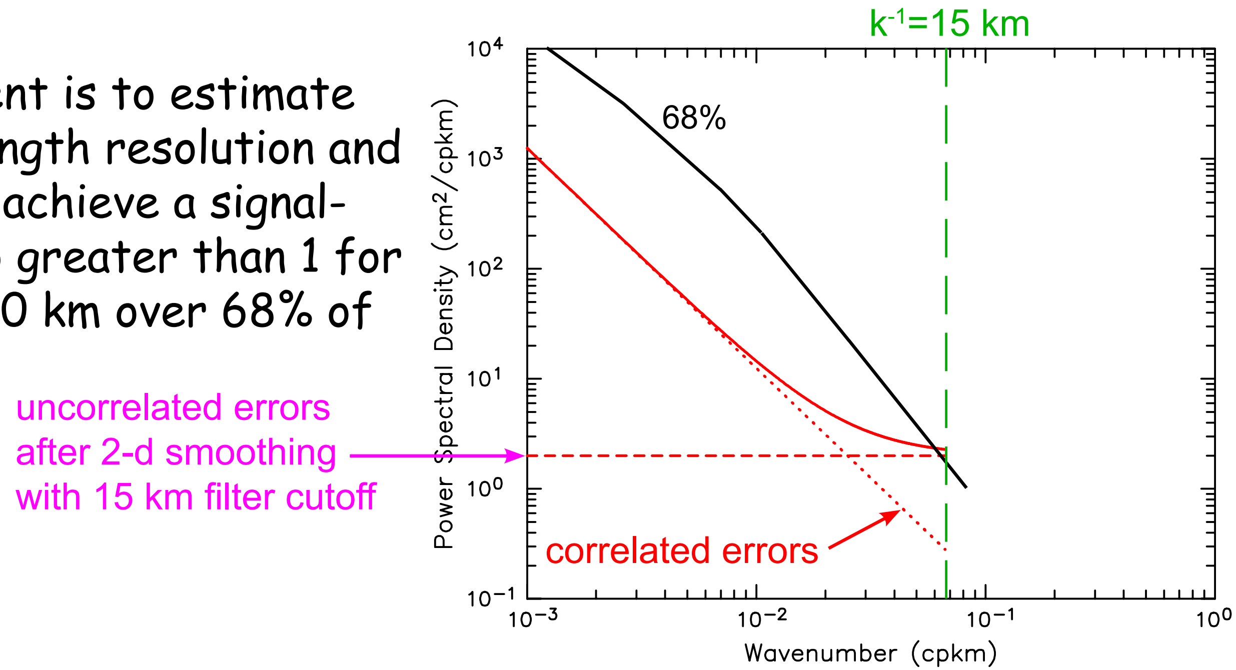

- This spectral specification of errors can be "reverse engineered" to show that the standard deviation of uncorrelated SSH measurement errors is $\boxed{\sigma_{\epsilon_h} = 2.74 \text{ cm}}$

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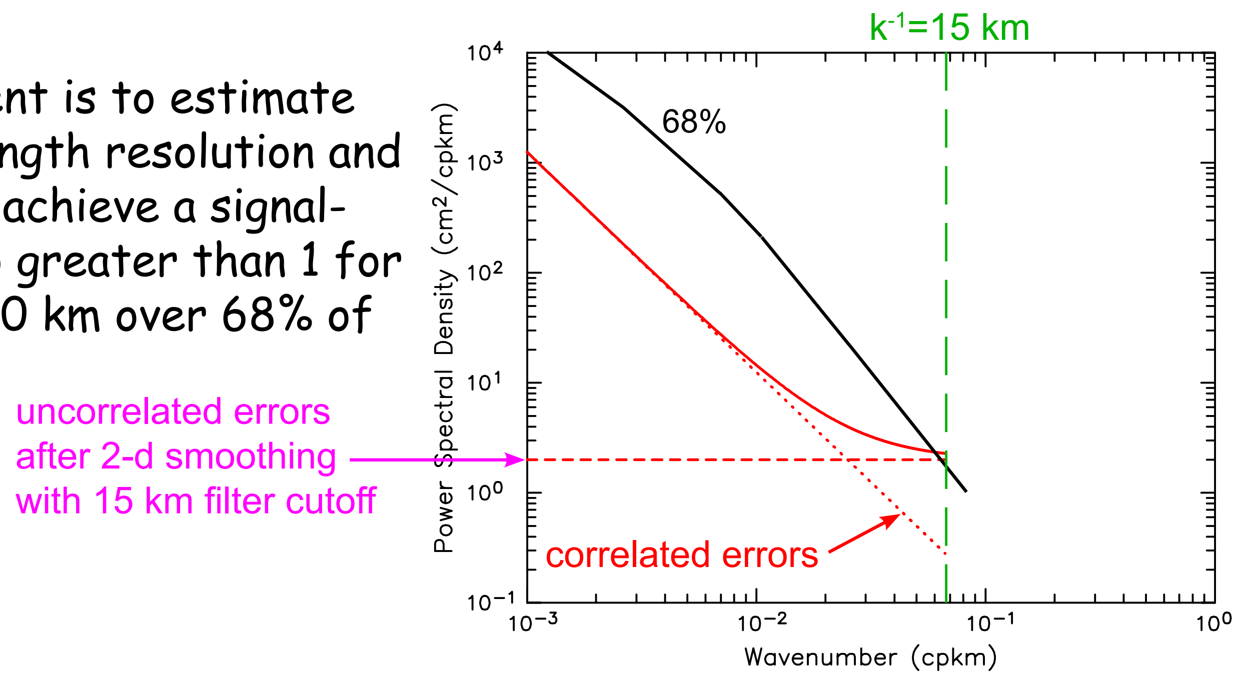

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Standard deviation of errors of each velocity component: $\boxed{\sigma_{\epsilon_{vg}} = \sigma_{\epsilon_{ug}} = 2.17 \text{ m/s}}$

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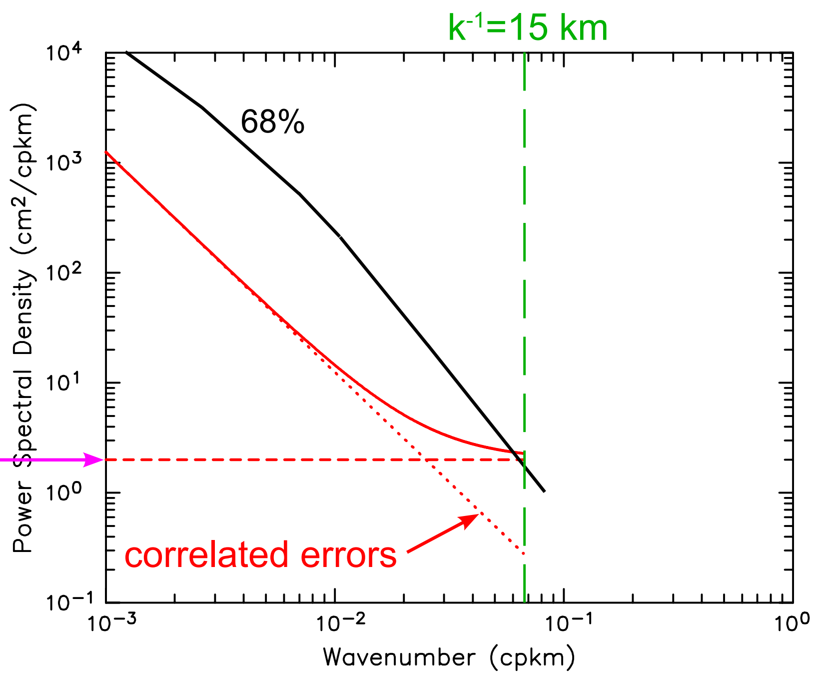

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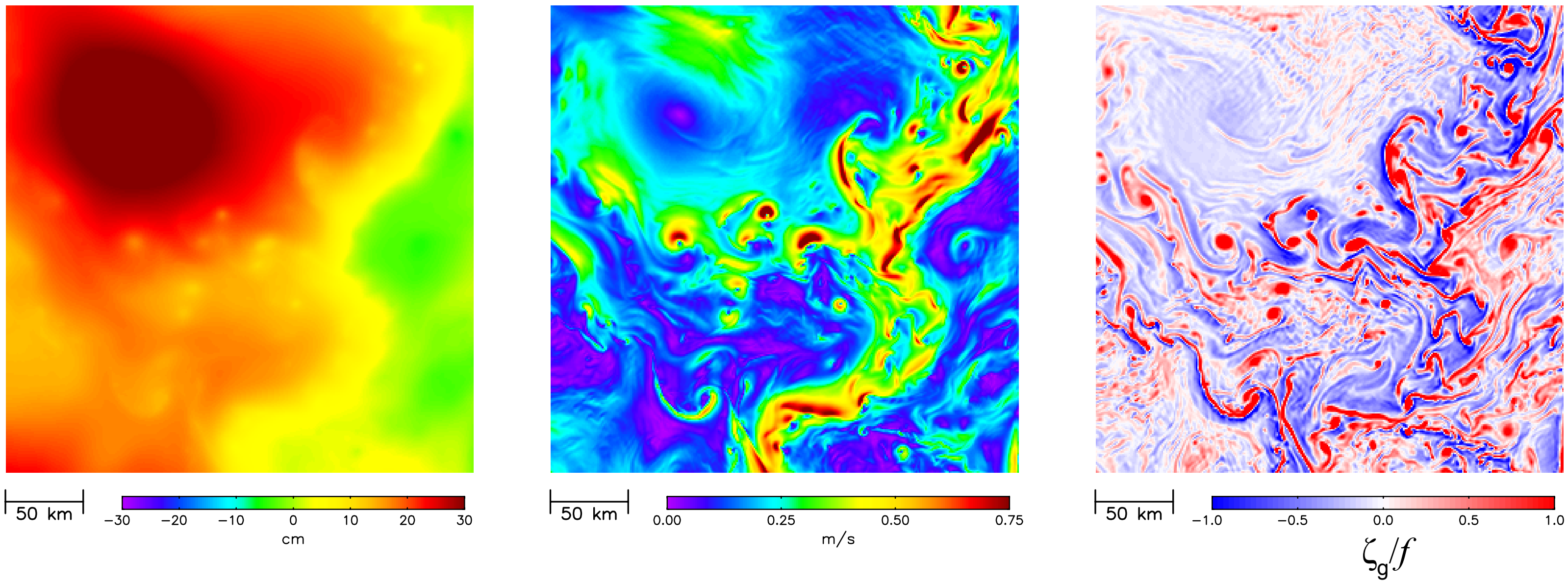
Standard deviation of vorticity errors: $\boxed{\sigma_{\epsilon_{\zeta_g}} = 39f}$

SSH, Geostrophic Speed and Geostrophic Vorticity Unsmoothed with the 1 km Resolution of SWOT

Error Free Measurements



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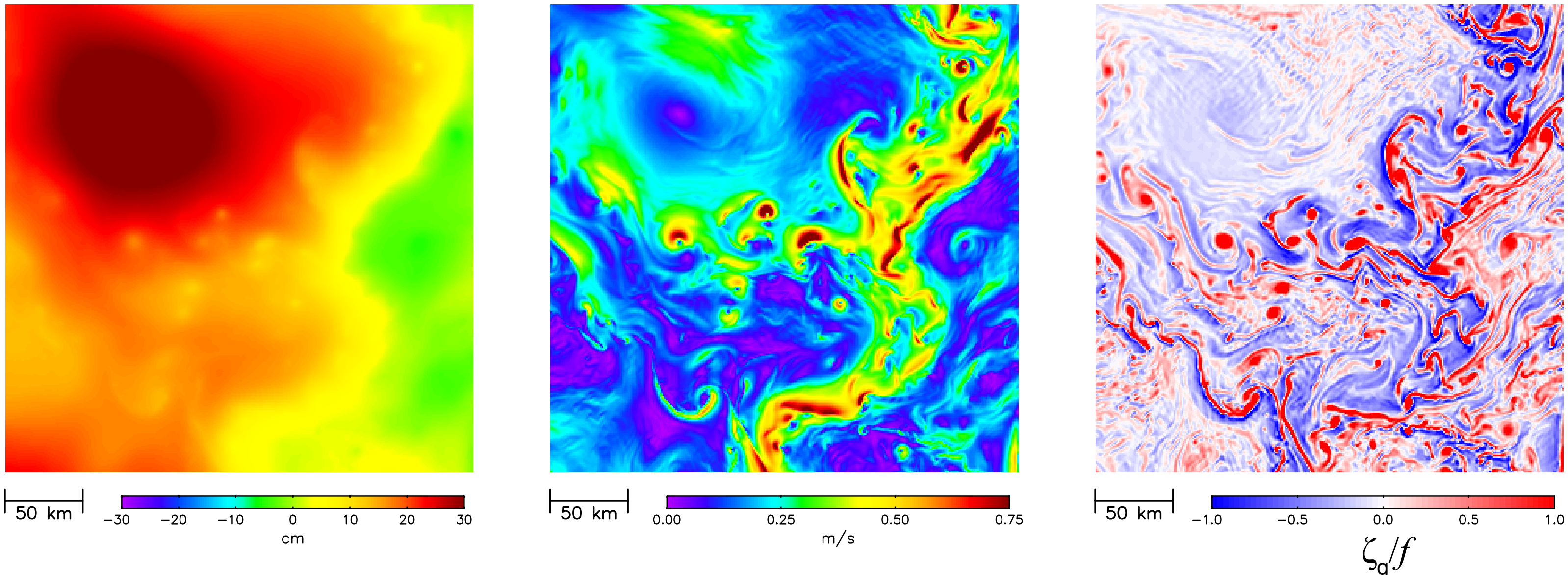
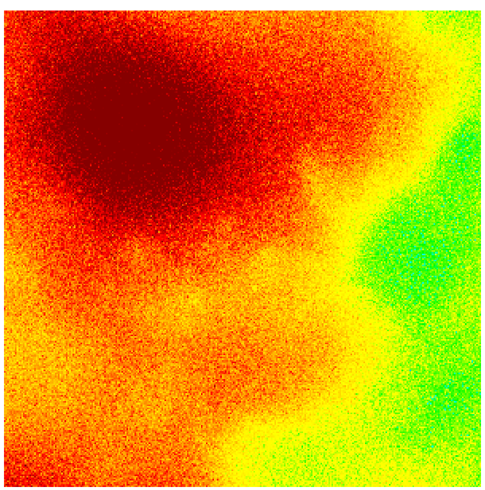


With 2.74 cm RMS Measurement Errors



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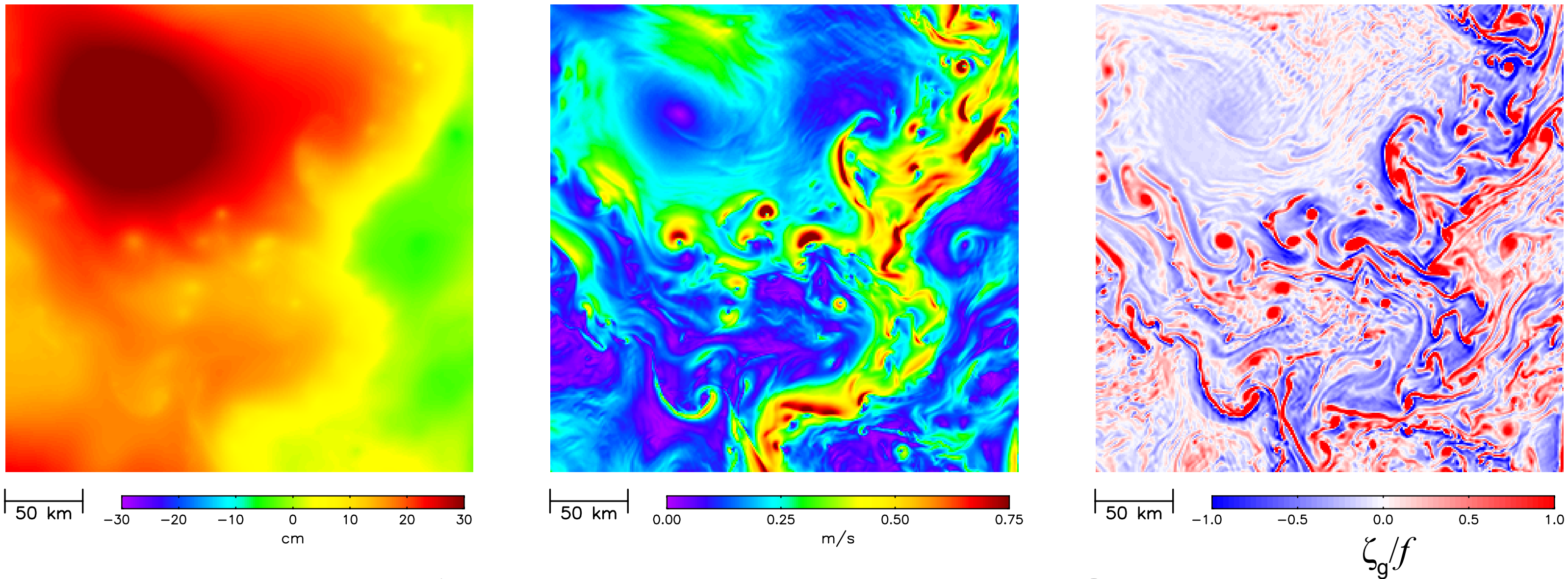

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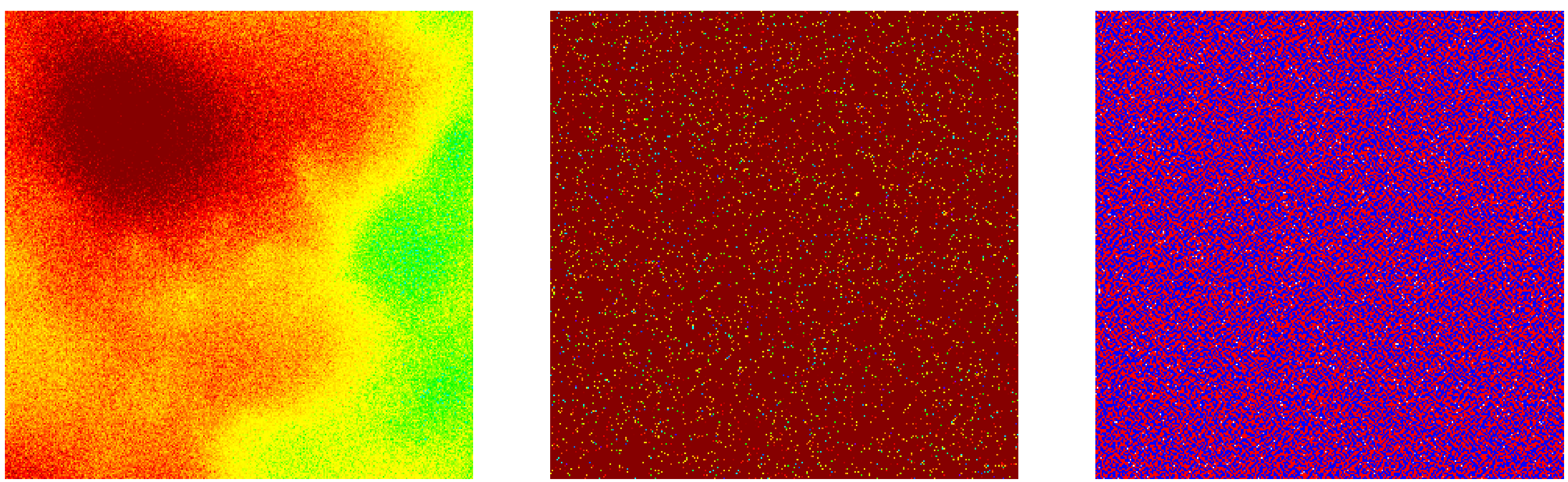

Procedure for Defining Resolution Capability

1. Time-averaged maps of geostrophic velocity and vorticity were constructed 3 different ways from twice-daily snapshots of model output:

   "noise only" = Signal plus measurement noise over the full CCS model domain

   "sampling errors only" = Error-free signal sampled only within the swaths

   "noise + sampling errors" = Signal plus measurement noise sampled only within the swaths

2. Each time-averaged field was smoothed spatially to reduce the effects of measurement and sampling errors.

3. The errors of each set of 3 fields were computed by subtracting the error-free true space-time averages.

4. The resolution capability was defined to be the filter cutoff wavelength at which the Signal-to-Error variance ratio is >10.

   - This corresponds to a standard deviation ratio of 3.16

SWOT Estimates of Current Speed and Vorticity with 2.74 cm SSH Measurement Noise

Case 1:

Smoothed maps constructed from a snapshot of error-free and noisy SSH during a single SWOT overflight for the unrealistic case of sampling the entire Central CCS region.

This is the best that SWOT could possibly do on a single overpass with a swath that spans the full CCS model domain.

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Summary of Results

The best-case resolution capabilities for a single overpass are:

~30 km for geostrophic velocity

~50 km for geostrophic vorticity

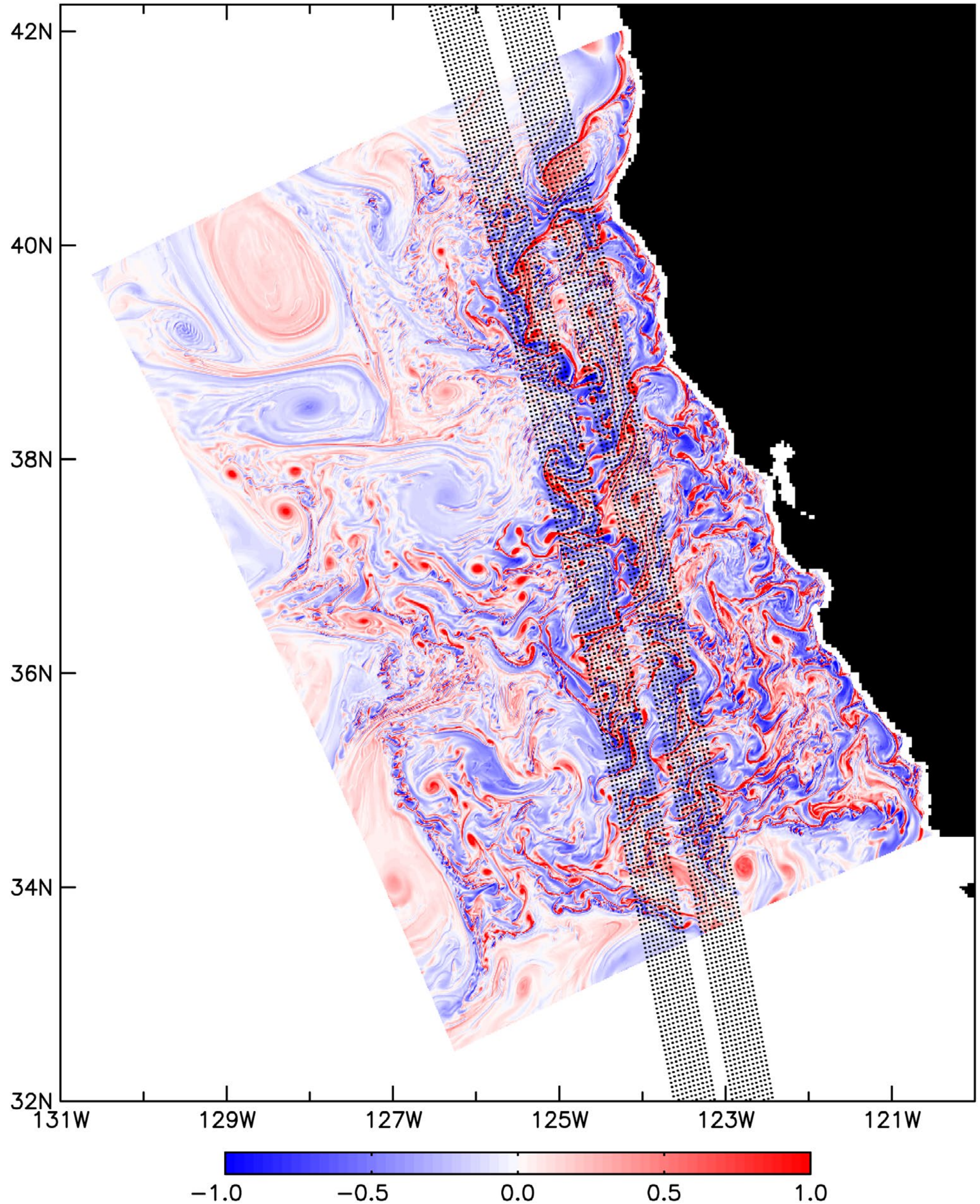
But note that each SWOT measurement swath is only 50 km wide. Edge effects from smoothing are therefore inevitable.

SWOT Estimates of Current Speed and Vorticity with 2.74 cm SSH Measurement Noise

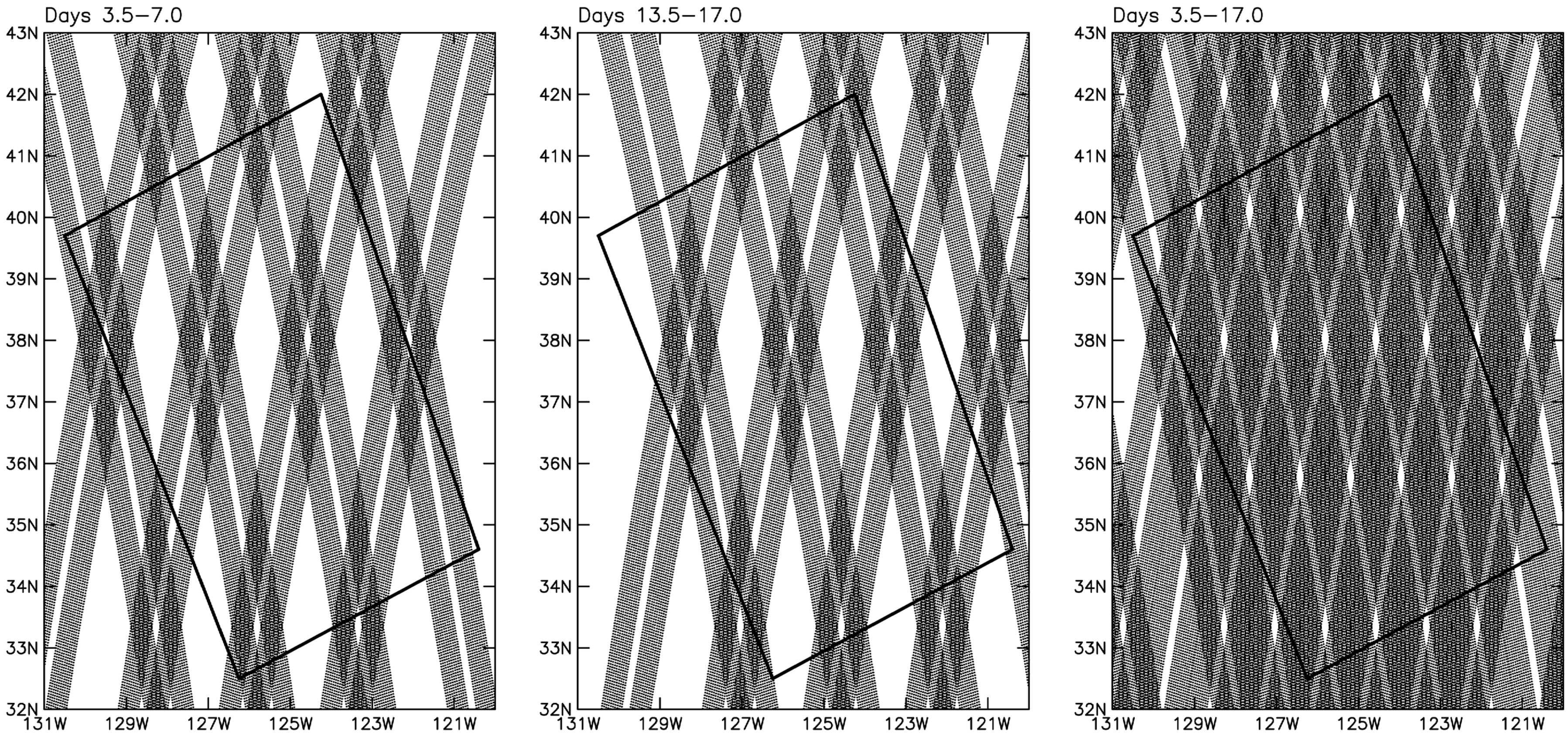
Case 2:

Smoothed maps constructed from 4-day and 14-day averaged error-free and noisy SSH over the full CCS domain for the realistic case of sampling only within the SWOT measurement swaths

SWOT Measurement Swath on a Single Overpass



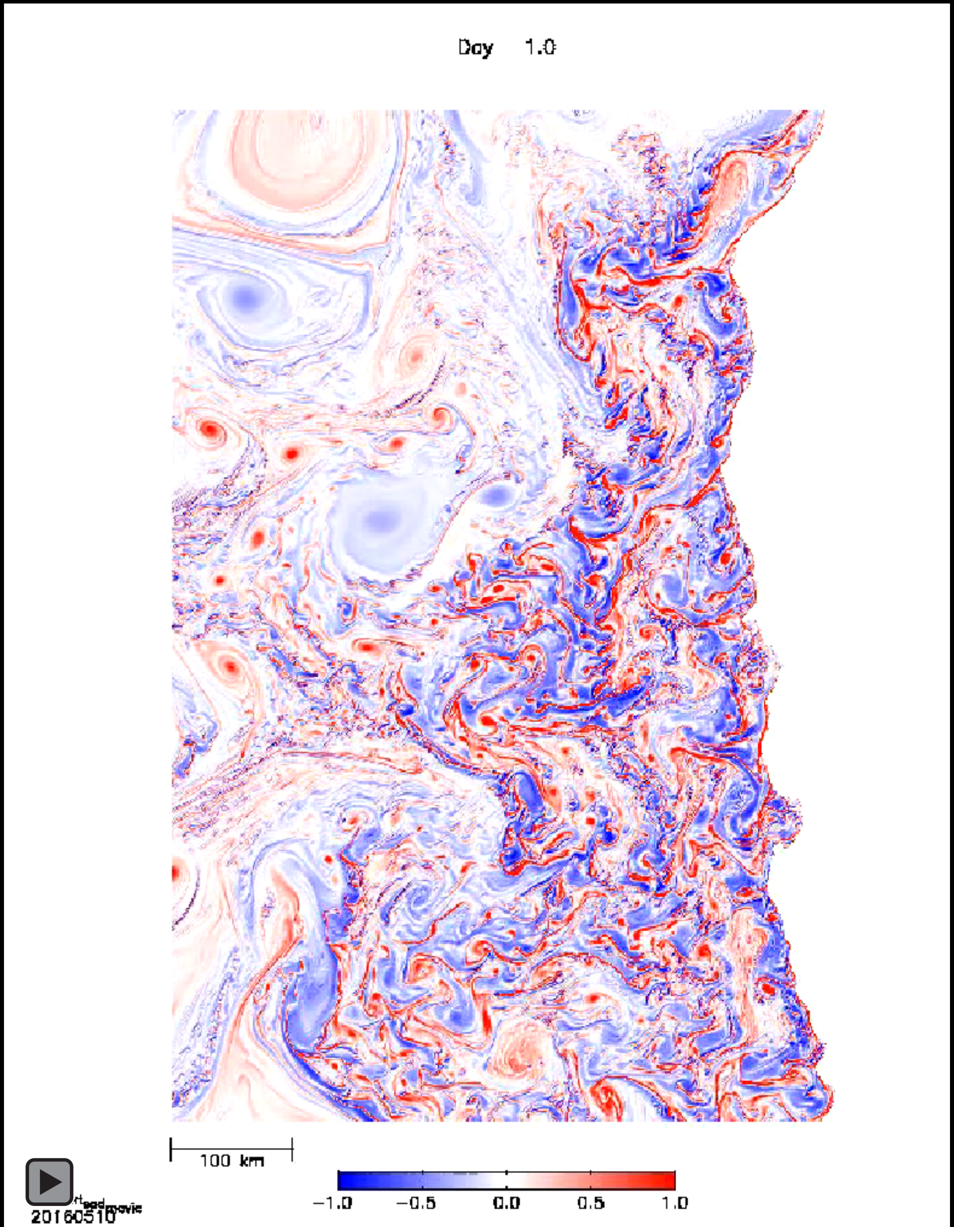
4-Day and 14-Day Subcycles in the CCS Region during Each 21-Day Exact Repeat Period



The sampling pattern over the CCS consists of:

1. A coarse set of intersecting swaths over a 4-day period.
2. A 6.5-day gap with no coverage.
3. Another coarse set of intersecting swaths over a 4-day period that is offset longitudinally from the first 4-day subcycle.
4. Another 6.5-day gap with no coverage.

31-Day Animation of ζ/f from ROMS Model of the CCS

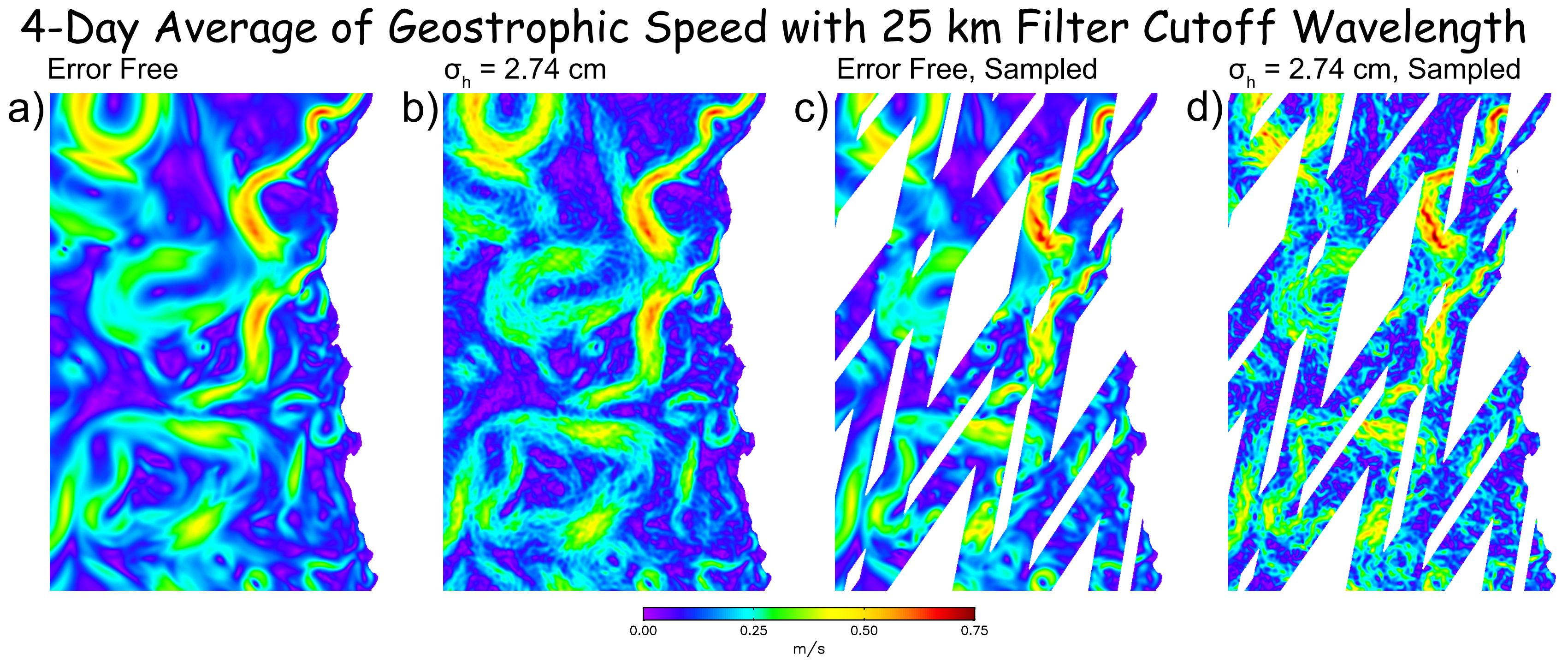


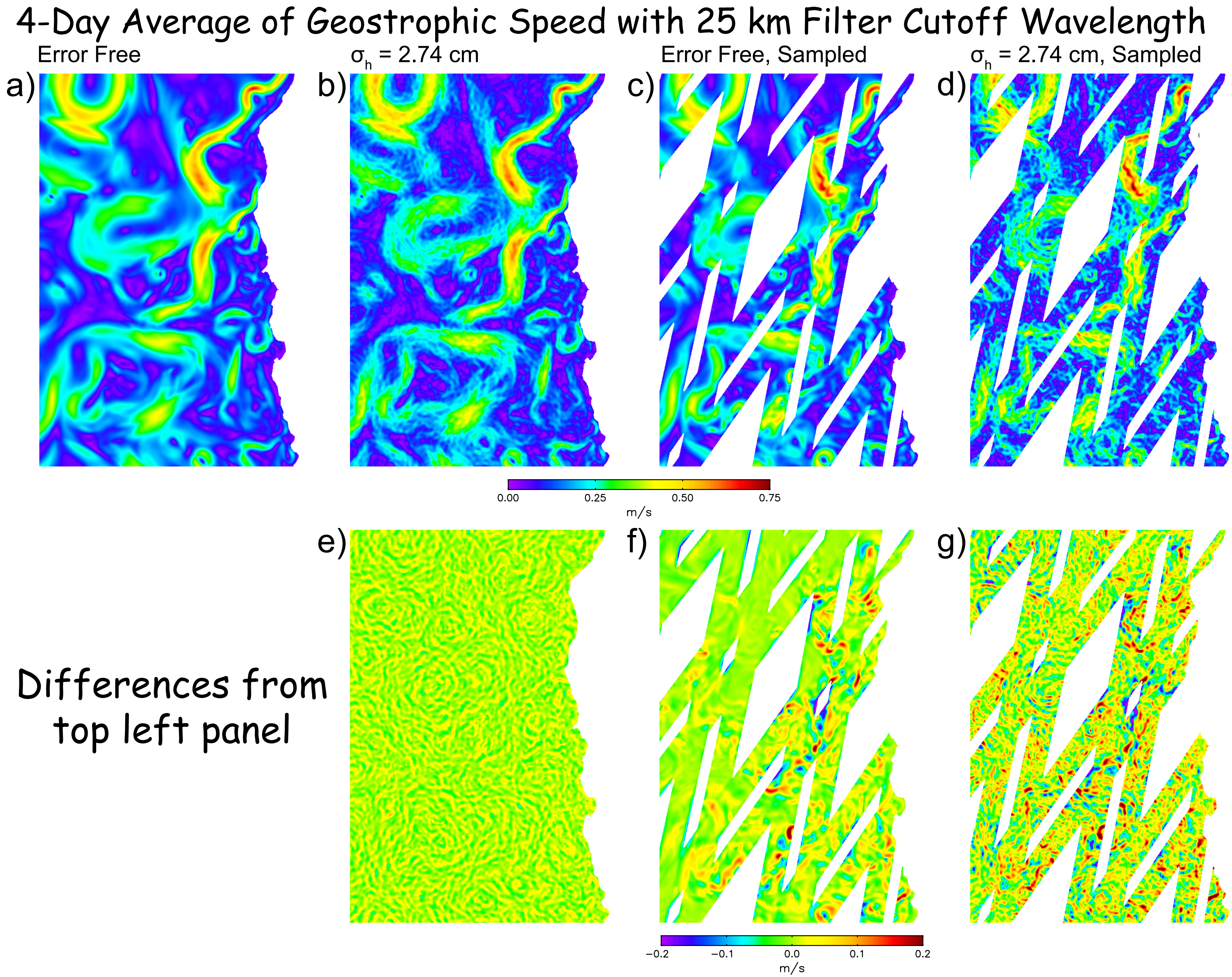
Sources of Sampling Errors

1. Spatial discontinuities across the edges of overlapping ascending and descending swaths because of the rapid evolution of submesoscale variability between the times of the satellite overpasses.

2. "Aliasing" effects from differences between the time average of the sampled fields and the true time-average fields because of the intermittent and discrete sampling:
   - Any given point in the CCS model domain is sampled only 0 to 2 times per 4 days and only 1 to 3 times per 14 days

3. Edge effects from smoothing with a half-power filter cutoff wavelength that is large compared with the 50 km width of each swath.


4-Day Average of Geostrophic Speed with 25 km Filter Cutoff Wavelength
Error Free
σ_h = 2.74 cm
Error Free, Sampled
σ_h = 2.74 cm, Sampled
a)
b)
c)
d)
0.00
0.25
0.50
0.75
m/s


4-Day Average of Geostrophic Speed with 25 km Filter Cutoff Wavelength
Error Free
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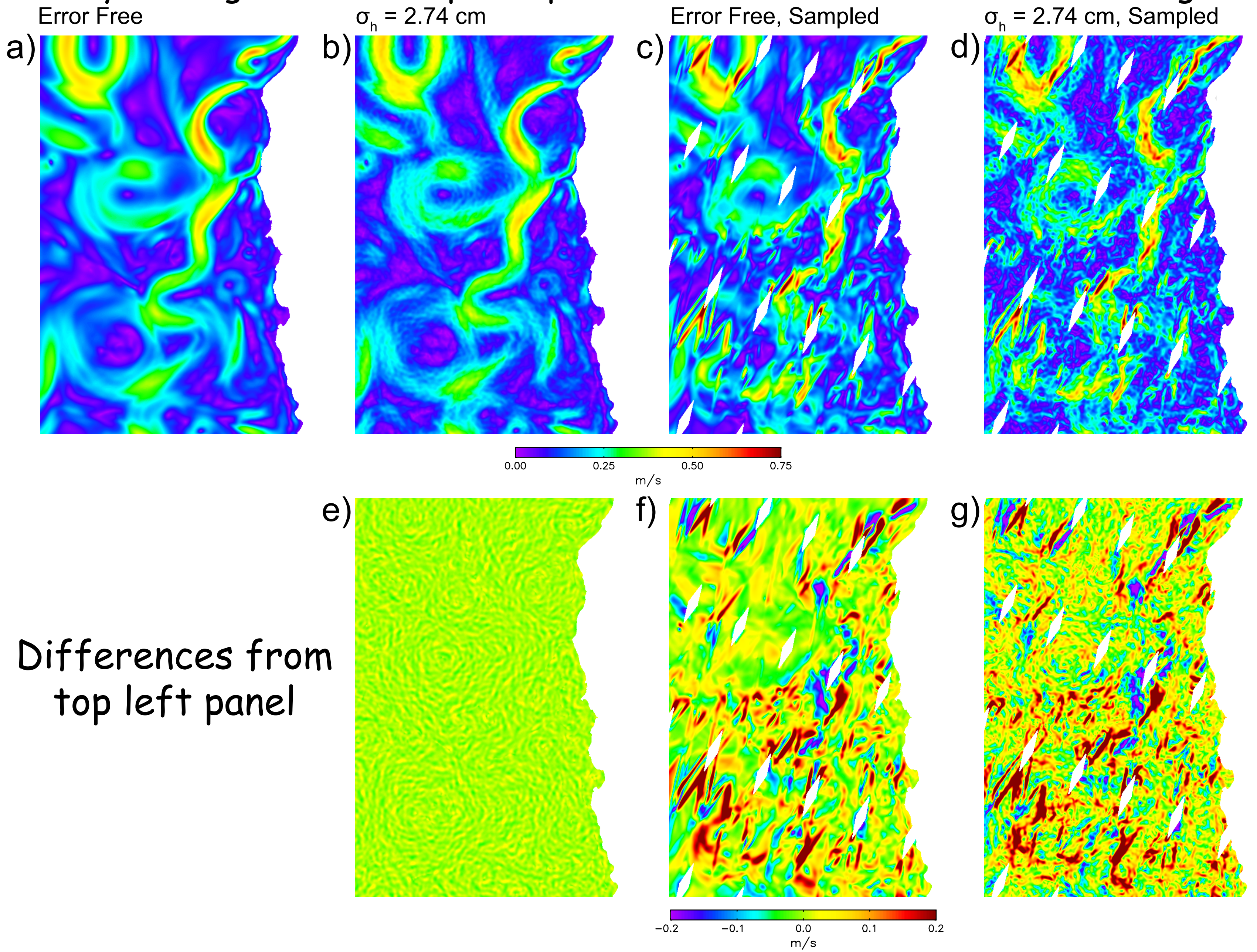
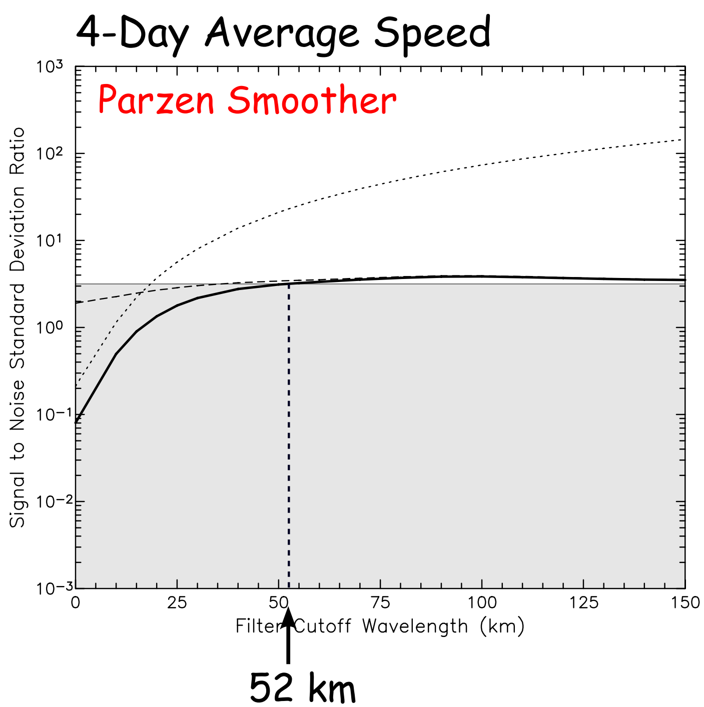
Error Free, Sampled
σ_h = 2.74 cm, Sampled
a)
b)
c)
d)
0.00
0.25
0.50
0.75
m/s
e)
f)
g)
Differences from top left panel
−0.2
−0.1
0.0
0.1
0.2
m/s

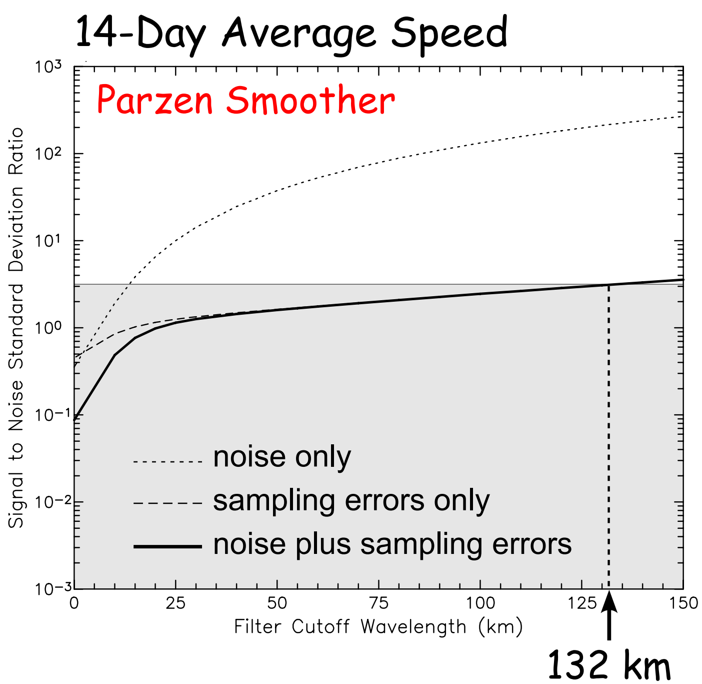
14-Day Average of Geostrophic Speed with 25 km Filter Cutoff Wavelength



Signal-to-Error Standard Deviation Ratio of Smoothed SWOT Estimates of Geostrophic Speed

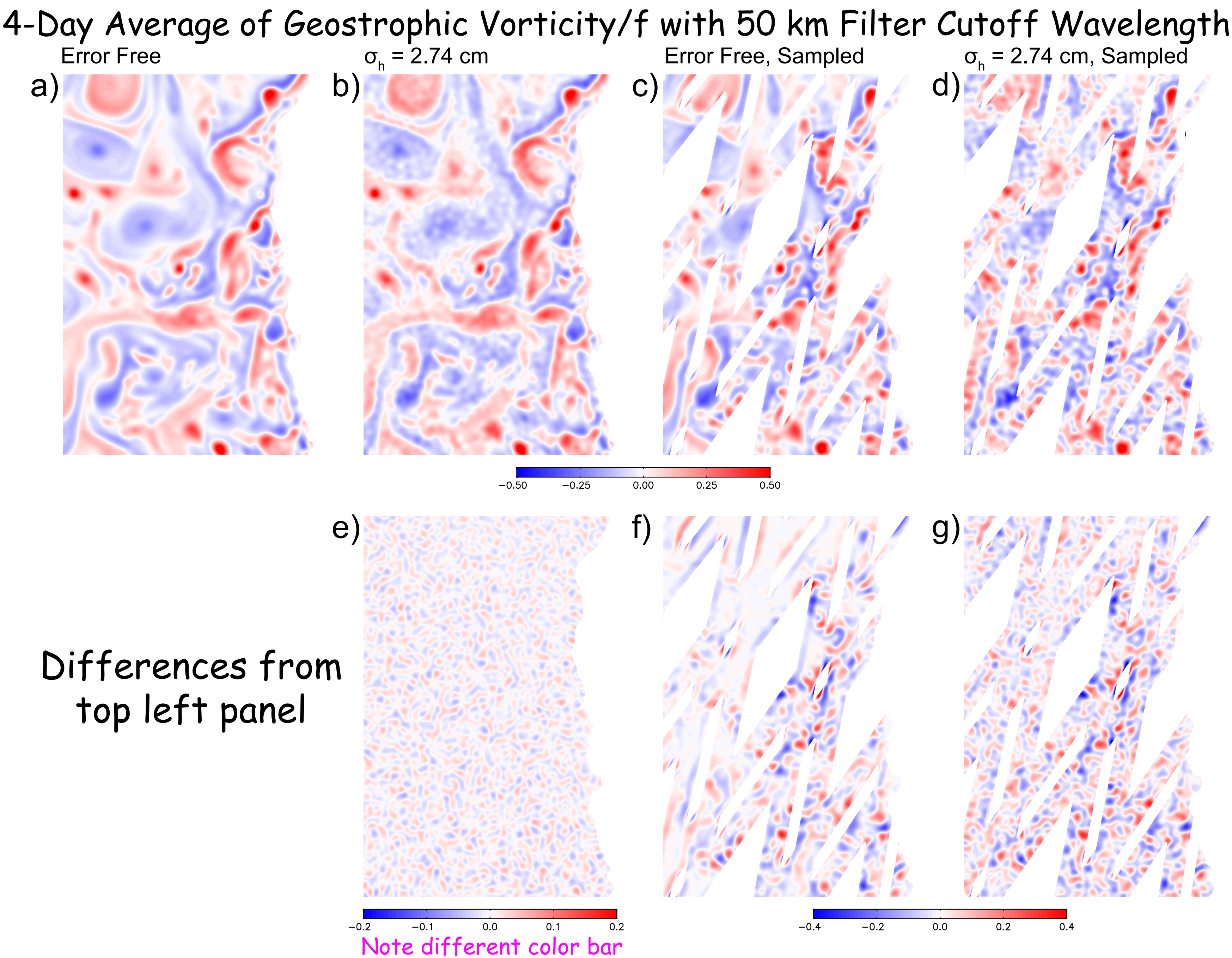
Case 2: Measurement and Sampling Errors





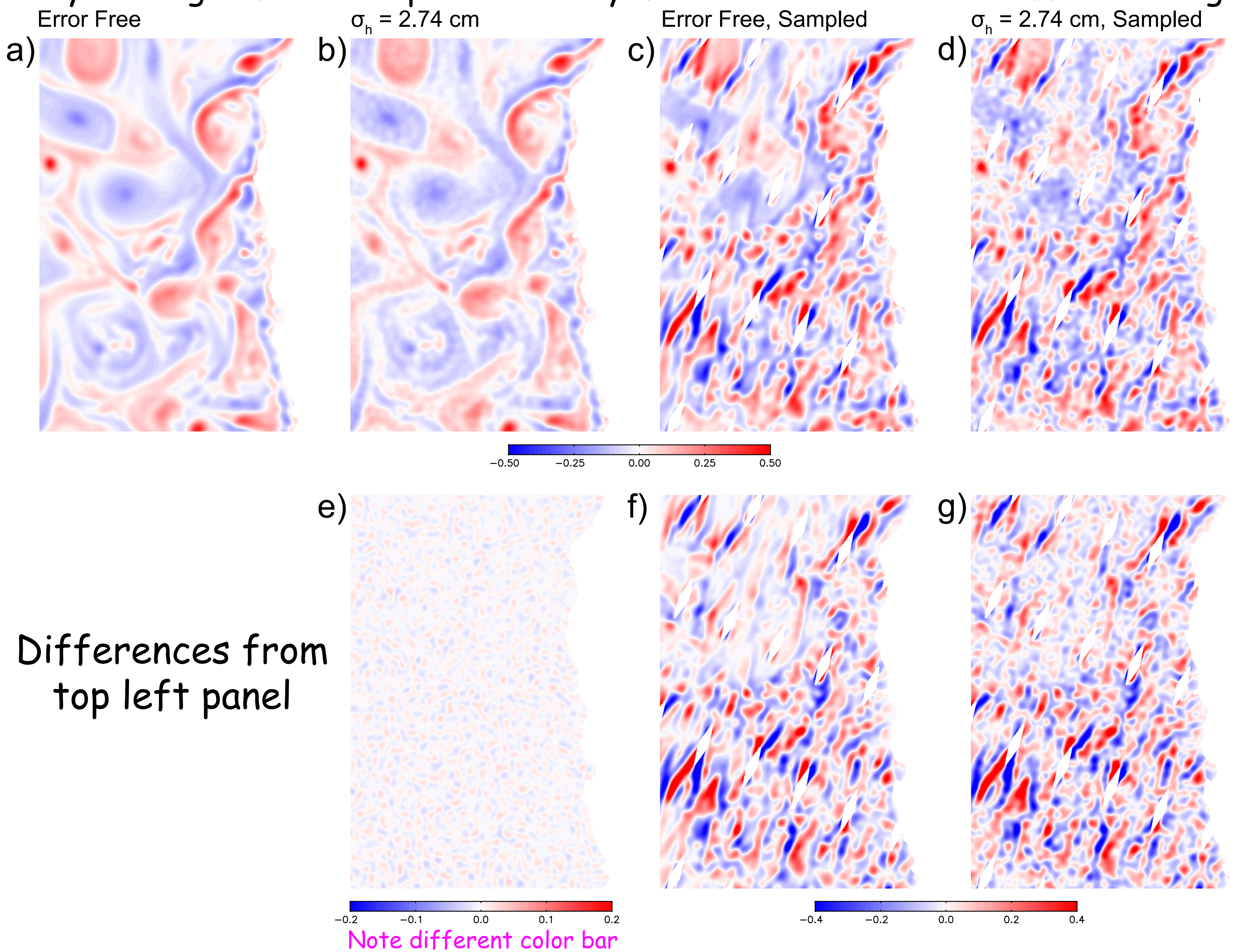
Resolution is limited by sampling errors rather than measurement errors.

The resolution capability would be higher in regions of more energetic mesoscale variability, hence larger signal-to-error ratio.



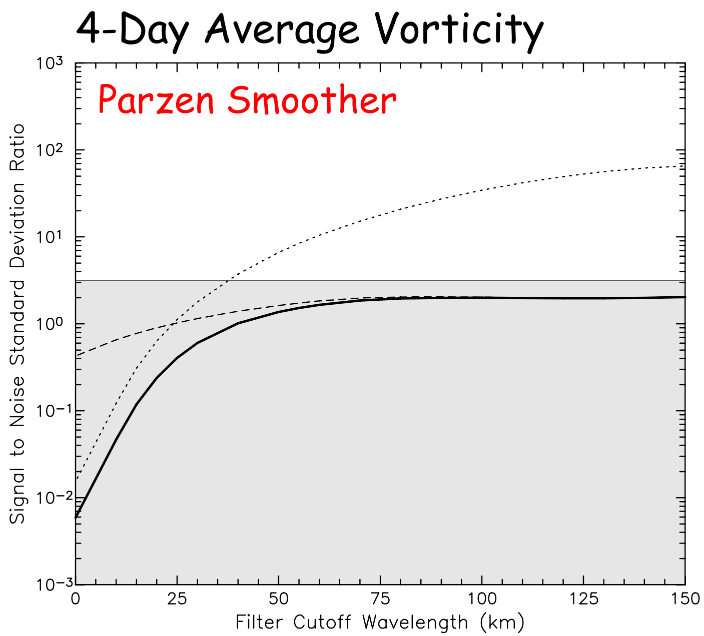
4-Day Average of Geostrophic Vorticity/f with 50 km Filter Cutoff Wavelength
Error Free
σ_h = 2.74 cm
Error Free, Sampled
σ_h = 2.74 cm, Sampled
a)
b)
c)
d)
−0.50
−0.25
0.00
0.25
0.50
e)
f)
g)
Differences from top left panel
−0.2
−0.1
0.0
0.1
0.2
Note different color bar
−0.4
−0.2
0.0
0.2
0.4

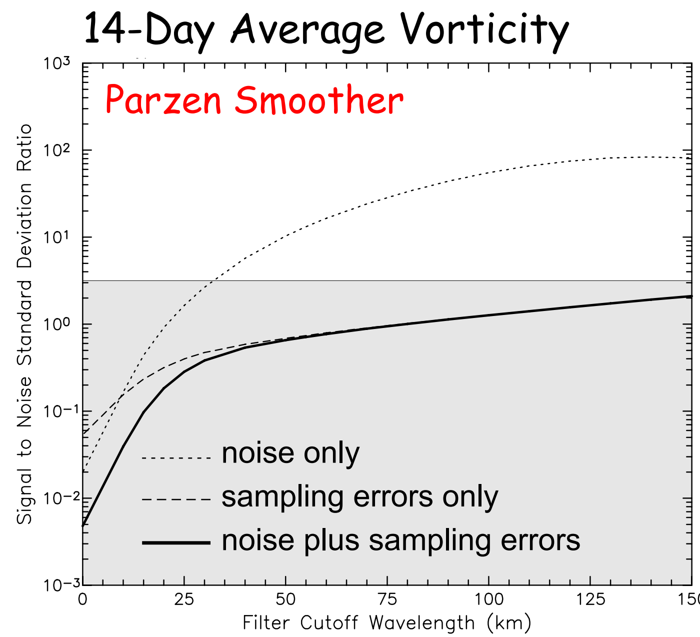
14-Day Average of Geostrophic Vorticity/f with 50 km Filter Cutoff Wavelength



Signal-to-Error Standard Deviation Ratio of Smoothed SWOT Estimates of Geostrophic Vorticity

Case 2: Measurement and Sampling Errors



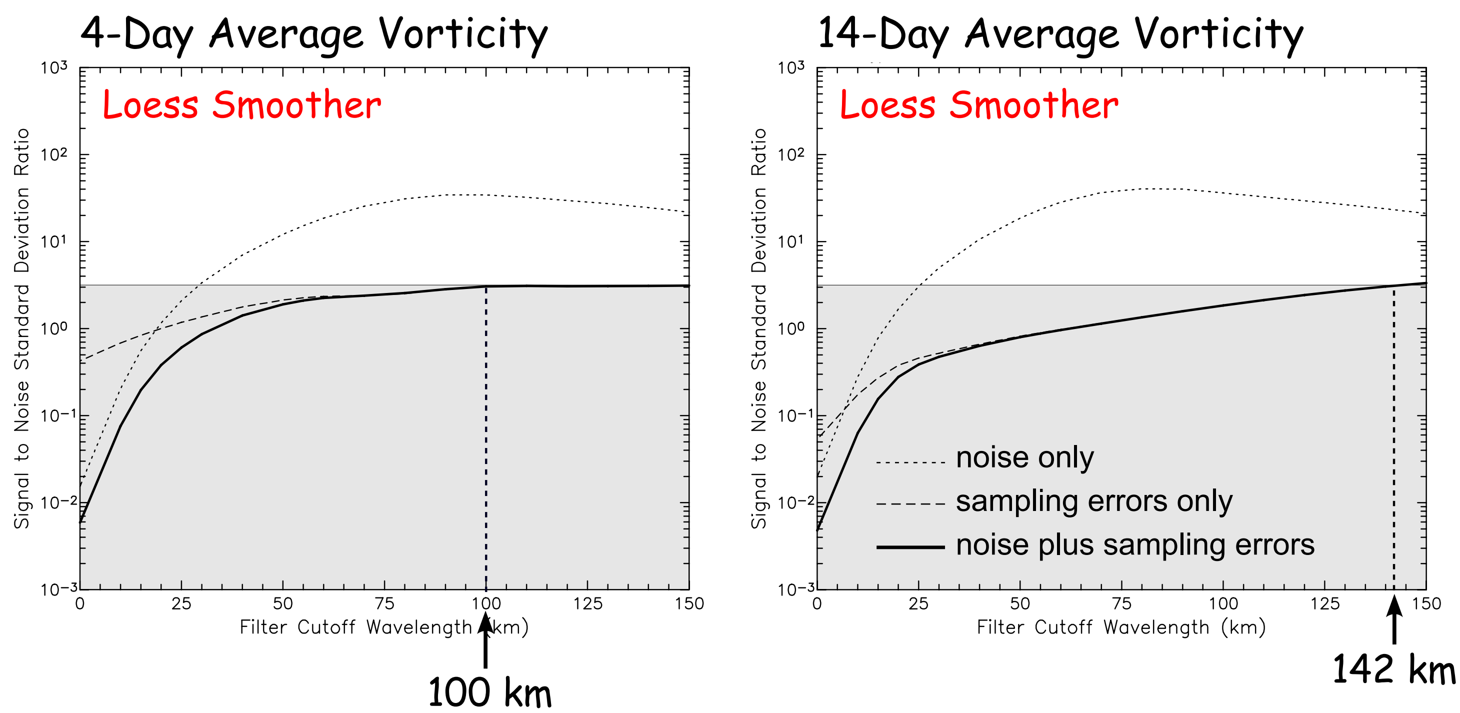


Resolution for vorticity is even more severely limited by sampling errors.

Note again that the resolution capability would be higher in regions of more energetic mesoscale variability, hence larger signal-to-error ratio.

Signal-to-Error Standard Deviation Ratio of Smoothed SWOT Estimates of Geostrophic Vorticity

Case 2: Measurement and Sampling Errors



The conclusions about resolution capability can be improved somewhat with the use of more sophisticated smoothing procedures.

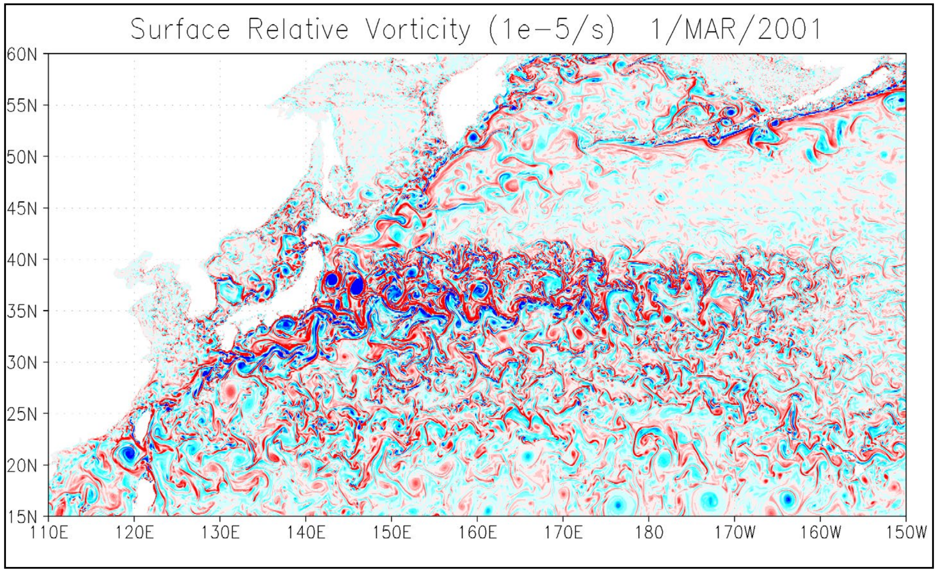
Note also that the threshold of Signal-to-Error ratio of 3.16 used here to define resolution capability is a subjective choice.

Simulated SWOT Estimation of Vorticity in the Kuroshio Extension

(from Qiu, Chen, Klein, Ubelmann, Fu & Sasaki, 2016, J. Phys. Oceanogr.)

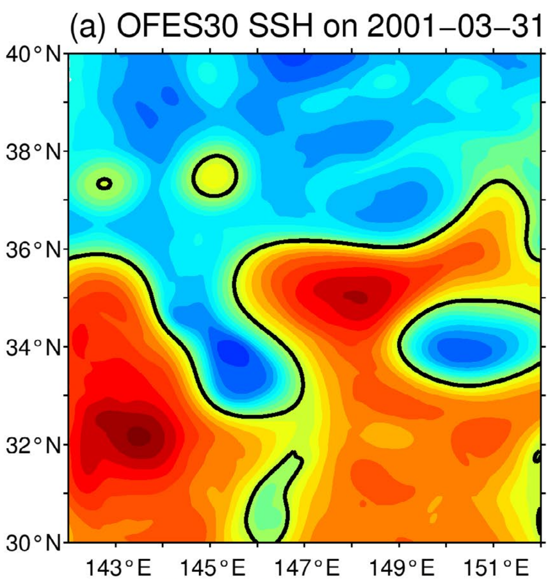
OFES 1/30° N Pacific OGCM Simulation:

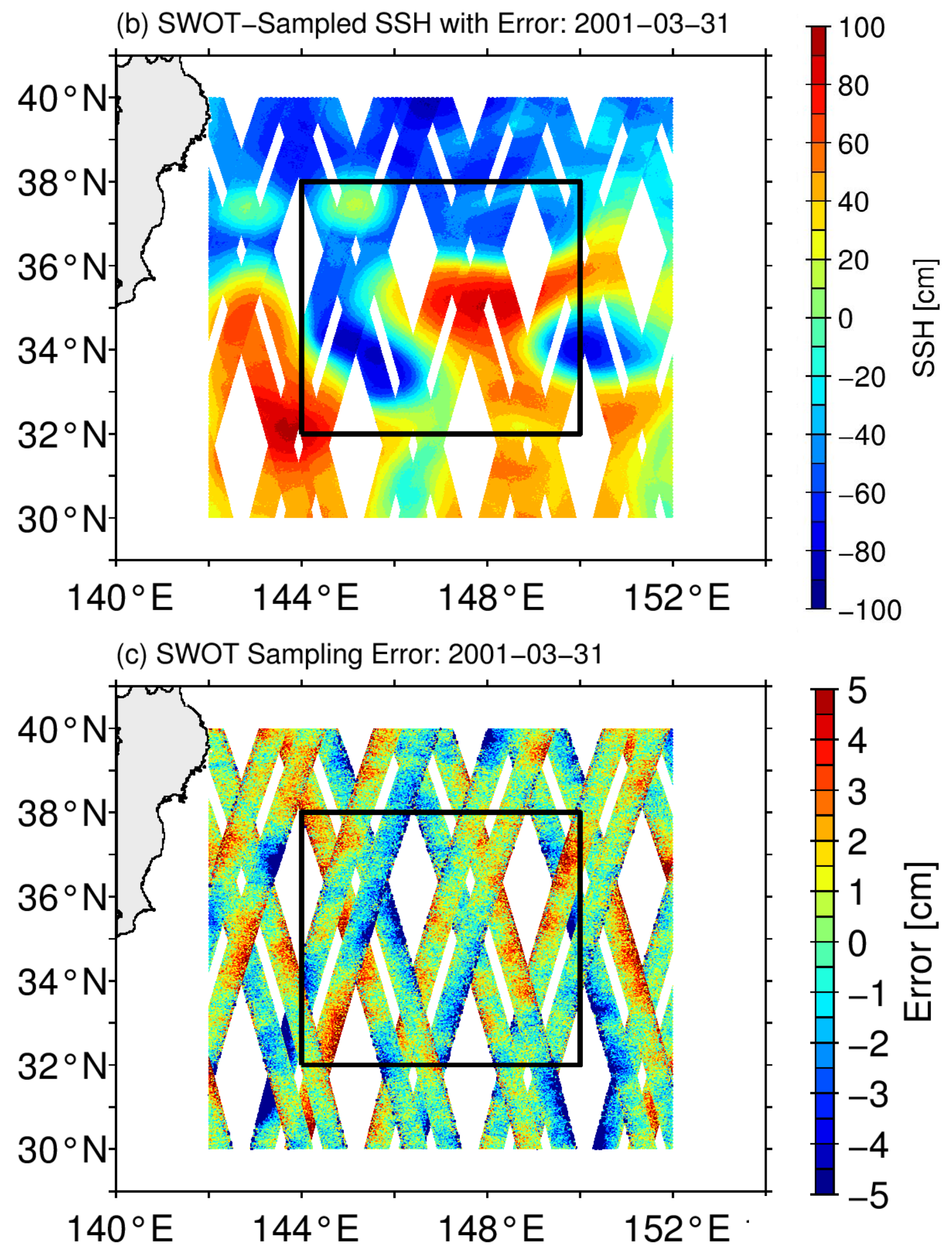
- **SWOT-equivalent 3-km horizontal grid resolution; 100 vertical levels (60 in upper 500 m)**
- **Model domain 100°E-70°W, 20°S-66°N**
- **Initialized with a coarser 1/10° North Pacific simulation on 1 January 2000**
- **Forced by JRA-25 6-hourly reanalysis data (1° resolution)**
- **Analysis of daily-mean w & ζ field of 2001-2002**



Sasaki, Klein, Qiu & Sasai (2014, Nature Comm.)

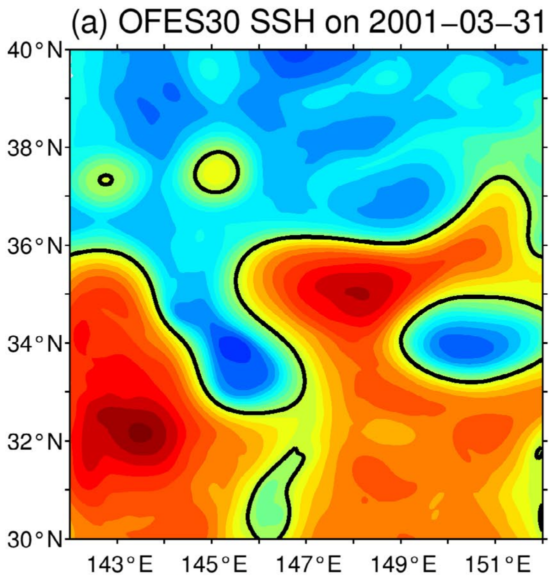
SWOT Simulator Sampling of SSH During a 4-Day Subcycle

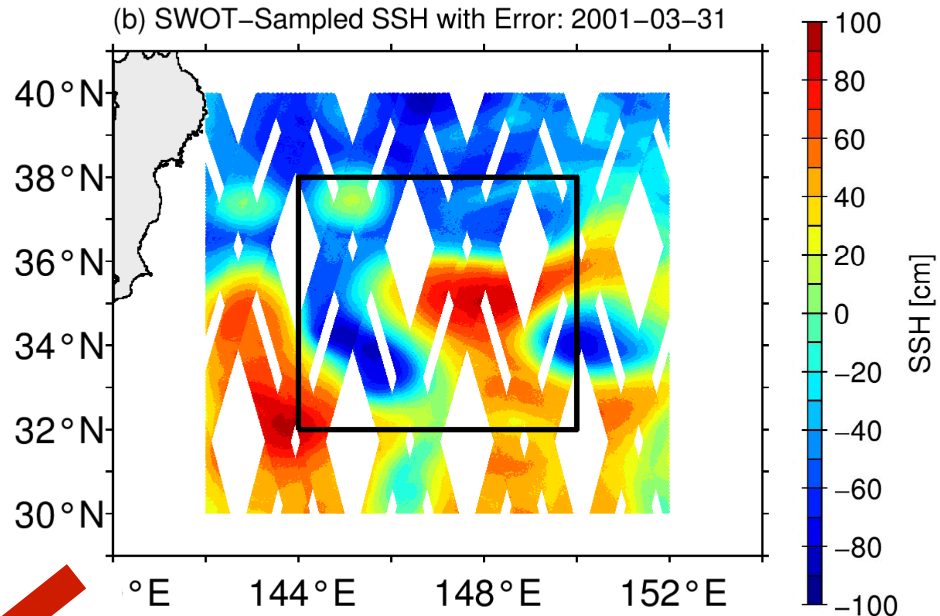


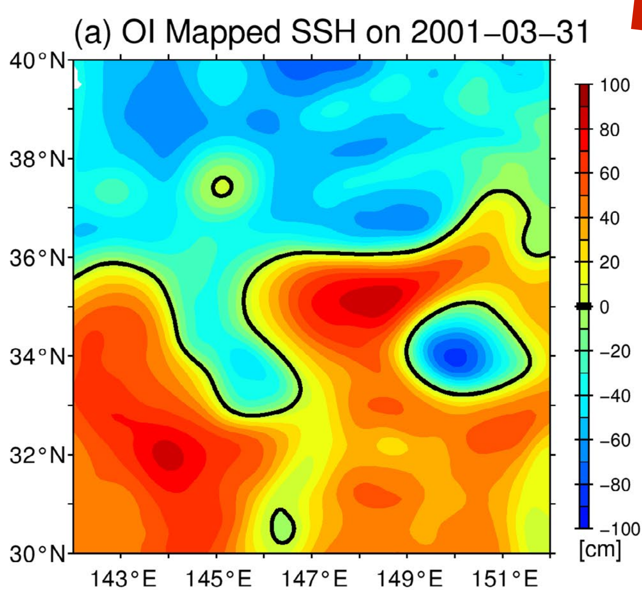


- Spatial discontinuities are due to time differences between swaths and larger measurement errors toward the edges of the swath.
- Measurement errors have a larger impact on small-scale SSH signals because of larger noise-to-signal ratio.

Space-Time Objective Mapping of SSH

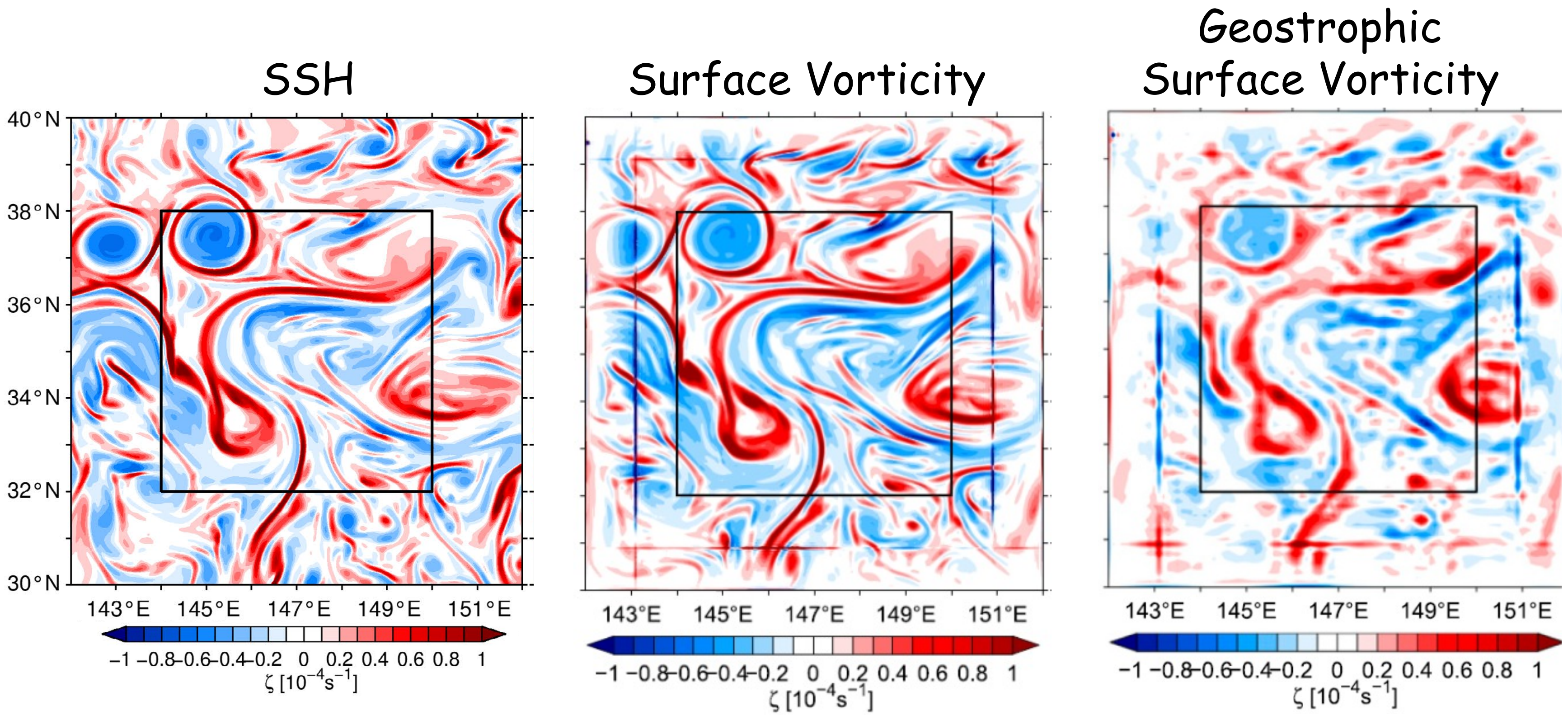






- Objective analysis based on an exponential covariance function with e-folding scales of 50 km and 3 days preferentially smears out the smaller-scale signals.
- Note that the large unsampled diamonds are filled by interpolation.
- The standard deviation of the SSH anomalies is reduced by 19.4%.

Geostrophic Vorticity Computed from Objectively Analyzed SSH

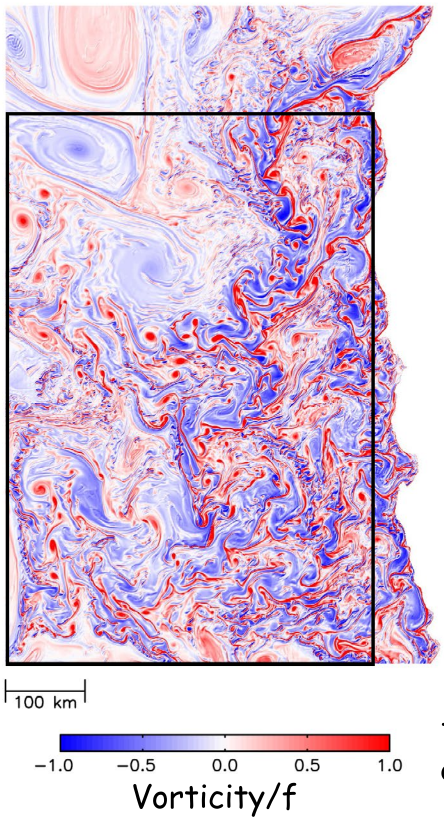


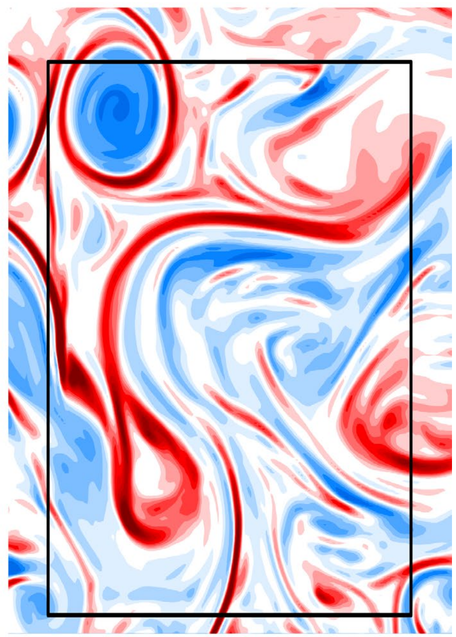
The correlation between vorticity and objective analysis estimates of geostrophic vorticity from simulated SWOT data drops from 0.79 to 0.69.

The lower correlation occurs preferentially at small scales.

Comparison of Vorticity in the CCS and the KE

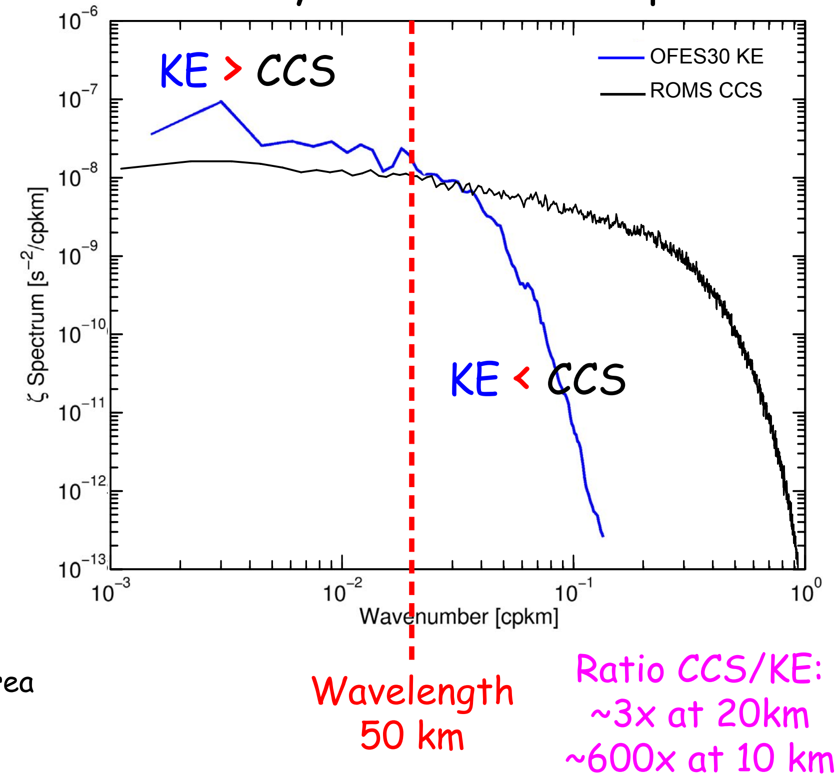
California Current System	Kuroshio Extension
ROMS 0.5 km grid	OFES 3 km grid
Snapshot of Vorticity/f	Daily Average Vorticity





The box on each map represents an area of 6° of latitude by 6° of longitude.

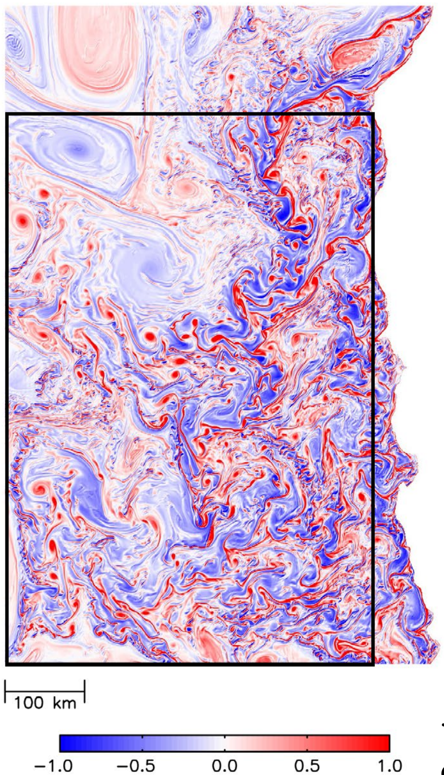
Vorticity Wavenumber Spectra



Compared with the CCS model, the KE model has higher variance at low wavenumbers (large scales), and lower variance at high wavenumbers (small scales). The noise and sampling requirements for simulated SWOT data from the KE model are therefore less stringent than from the CCS model.

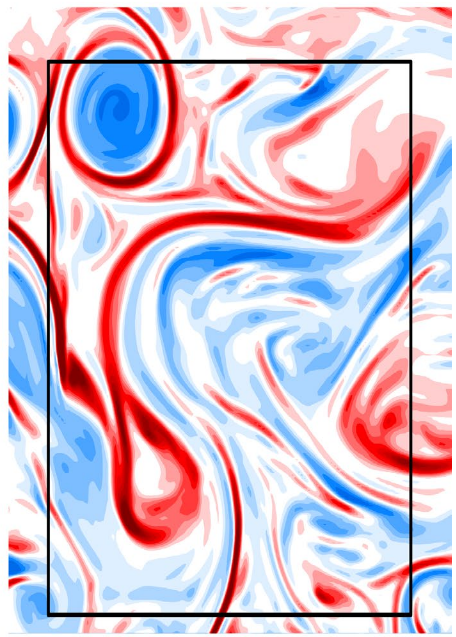
Comparison of Vorticity in the CCS and the KE

California Current System
ROMS 0.5 km grid
Snapshot of Vorticity/f



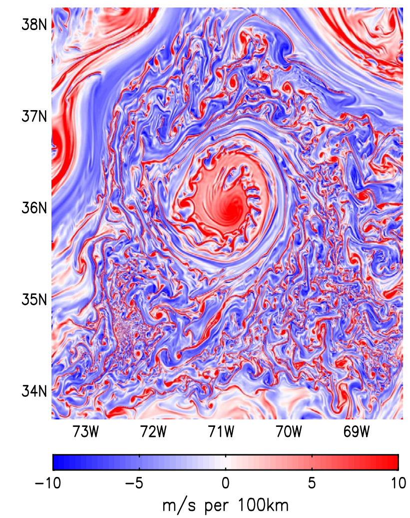
Vorticity/f

Kuroshio Extension
OFES 3 km grid
Daily Average Vorticity



The box on each map represents an area of 6° of latitude by 6° of longitude.

UCLA Model
of a Gulf Stream Eddy
ROMS 0.5 km grid
Snapshot of Vorticity
(Gula, Molemaker & McWilliams, 2015, J. Phys. Oceanogr.)



Vorticity

Sized to approximately the same scale as the left two figures.

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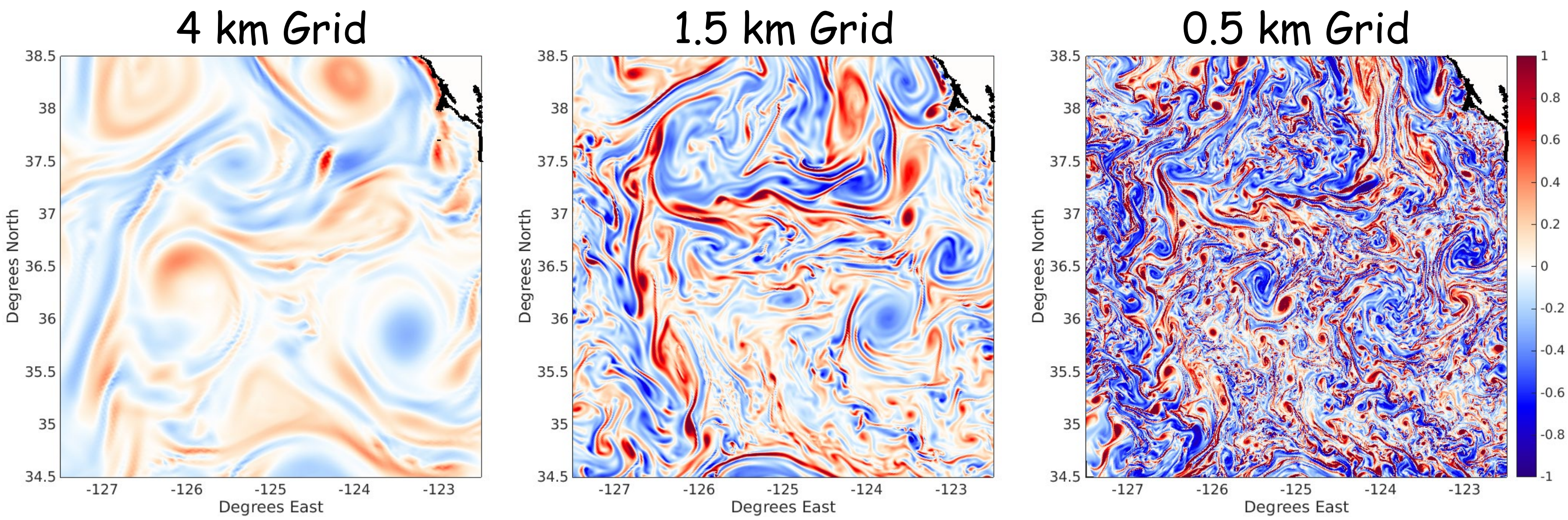
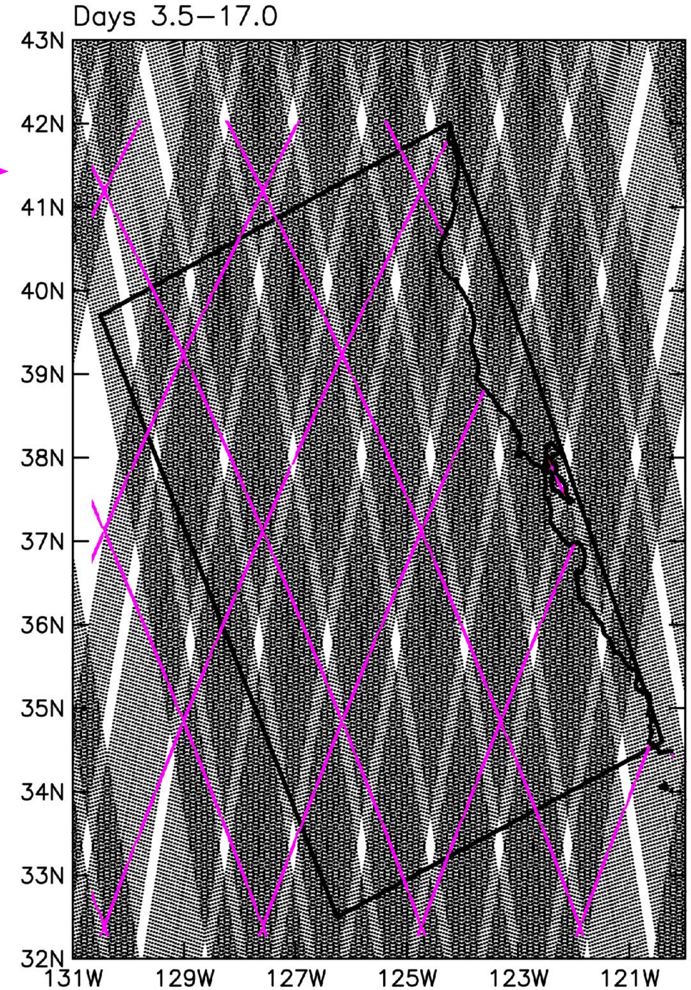
Vorticity/f from ROMS Models of the CCS with 3 Different Grid Resolutions



Model grid resolution matters!!

Conclusions

- SWOT will dramatically improve the accuracy and resolution of mesoscale SSH variability compared with present capabilities.
- SWOT estimation of geostrophic velocity and vorticity is much more challenging.
  - The SWOT SSH errors impose significant limitations on the resolution capability of SWOT estimates of the derivative variables u_g, v_g and ζ_g.
- Improved estimates of u_g, v_g and ζ_g can be expected in regions of energetic mesoscale variability where the signal-to-error ratio is higher for a given amount of smoothing.
  - Because mesoscale variability is only moderate in the CCS region, the results presented here may be more pessimistic than for some other regions.
- Assessment of the resolution capability of SWOT estimates of u_g, v_g and ζ_g is highly dependent on the choice of model.



Jason 10-day repeat ground tracks overlaid on 14 days of SWOT swaths.